Metal Foams as Compact High Performance Heat Exchangers

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Contents

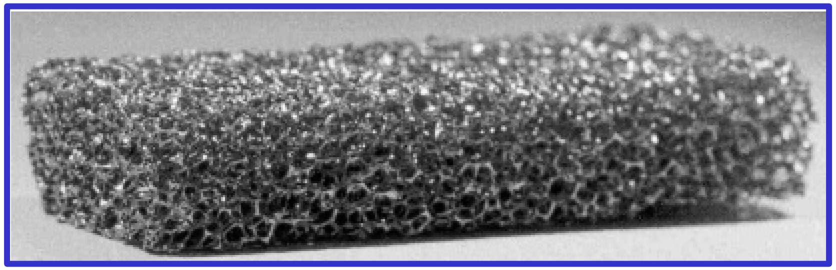
- Thermal management of IGBT's
- Metal foam heat exchanger configuration
- Experiments & Results
- Numerical Simulations
- Structure improvement
- Conclusions

Enhanced Heat Dissipation

- Thermal management of IGBT modules
  - Heat dissipation +100 W/cm^2
  - Low, uniform operating temperatures increase chip life
- Current configuration
  - Simple flat plate
  - High coolant velocity
  - Significant temperature gradients on the chip
- Possible improvements
  - Implement a highly conductive solid
  - Increase heat convection area
  - Better flow mixing structures

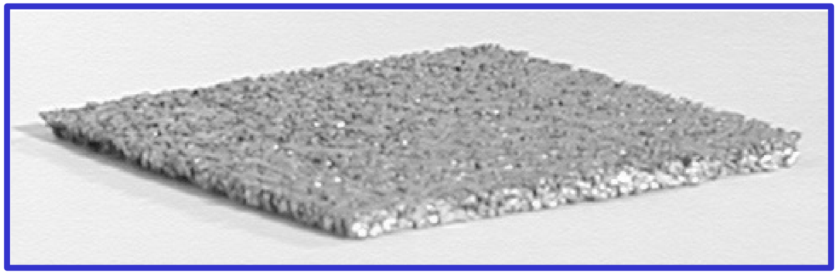
Aluminum Foam Properties

- High surface area to volume ratio
  - ~3000 m^2/m^3 uncompressed (natural form)
  - ~10,000 m^2/m^3 compressed
- Highly conductive solid (~218 W/m•K)
- Tortuous flow path
- Easily machined to final size



10 cm

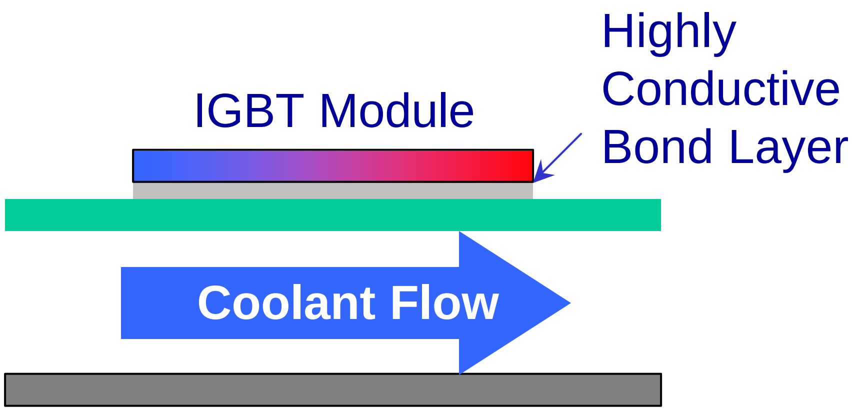
Aluminum foam in as-manufactured, unaltered state (92% porous)



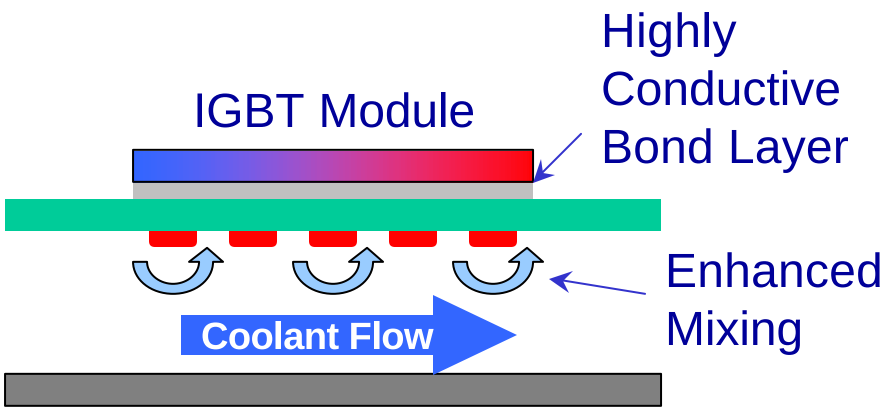
6.5 cm

Aluminum foam (73% porous) compressed by a factor of four

Typical Heat Exchanger Configurations



Open Channel

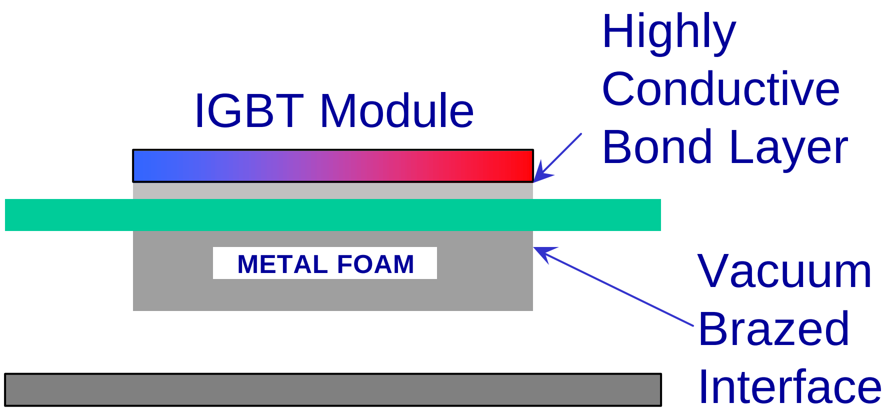


Turbulence Triggers

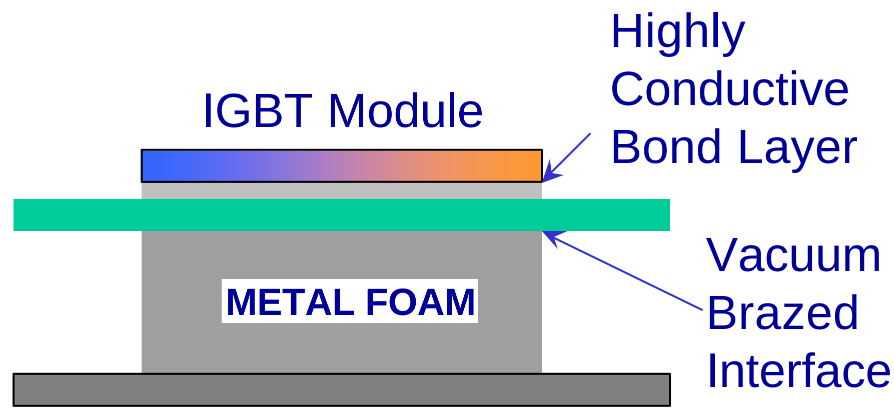
- Simplest design
- High flow velocity
- Mixing depends on upstream channel configuration

- Relatively simple
- Minimal increase in surface area
- Improved mixing through turbulence enhancers

Metal Foam Heat Exchanger Configurations



Foam / Open Channel Combination



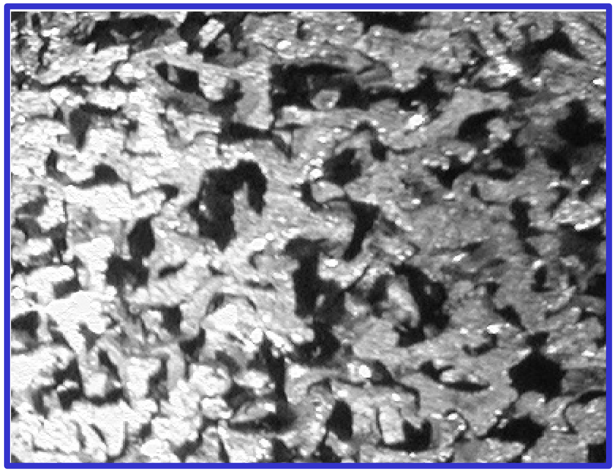
Metal Foam Insert

- Similar to turbulence enhancement array
- Lower flow resistance
- Less foam required
- Lower clogging likelihood

- Distributes heat throughout the coolant stream
- Provides a better basis for comparison of metal foam performance data

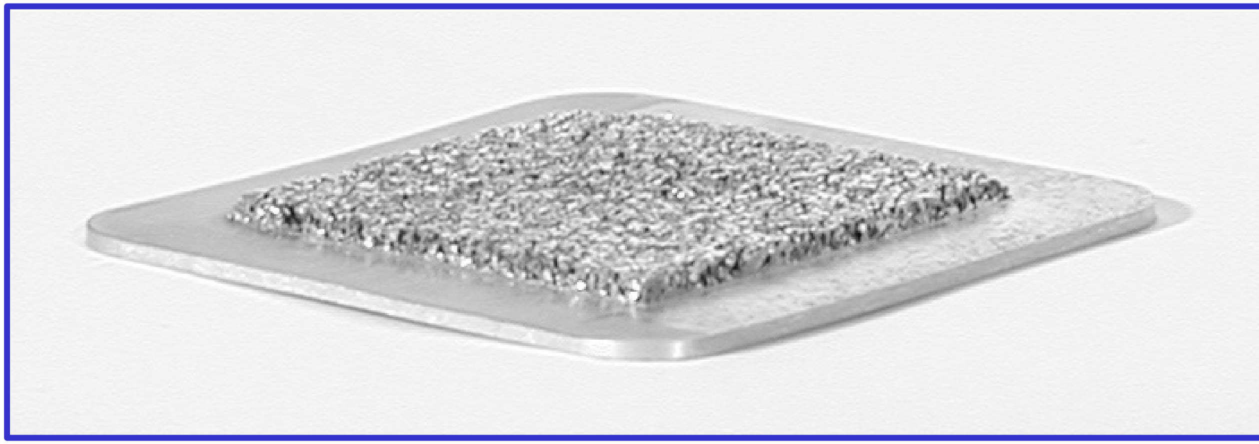
Compressed Foam Experimentation

- Utilize compressed foam—specific surface area ~10,000 m^2/m^3
- Porosities between 48 – 89%
- Coolant (water) flow velocities up to 2 m/s
- Convection coefficient (measured at plate) +150 $kW/m^2 \cdot K$



2 mm

Compressed Foam Close-up

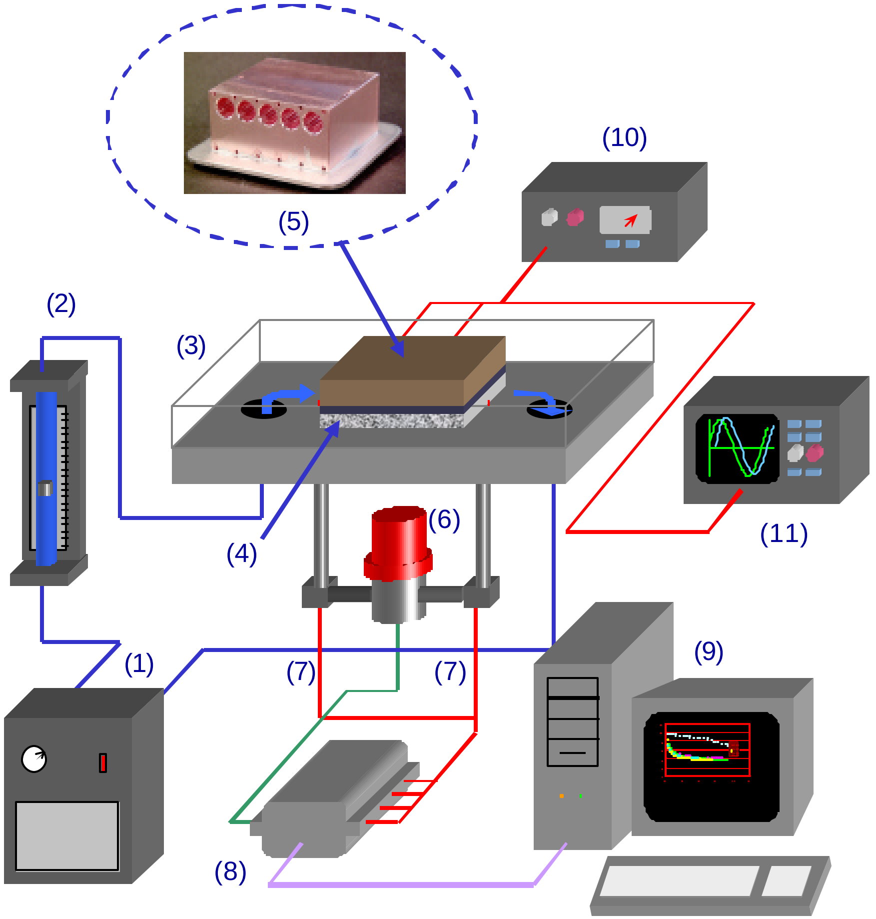


7 mm

Brazed Heater Assembly on a 18% AlSiC plate

Experimental Apparatus

- Pressure drop measurement
- Coolant temperature at various locations
- USB data acquisition device
  - Temperatures
  - Pressure
- 1200 W delivered by cartridge heaters
- Power input
  - Oscilloscope measurement
  - Temperature change in coolant



Pressure Drop and Heat Convection Coefficients

- Forchheimer-extended Darcy equation

$$\frac{\Delta p}{L} = \frac{m}{K} v + \frac{c_F}{\sqrt{K}} r v^2$$

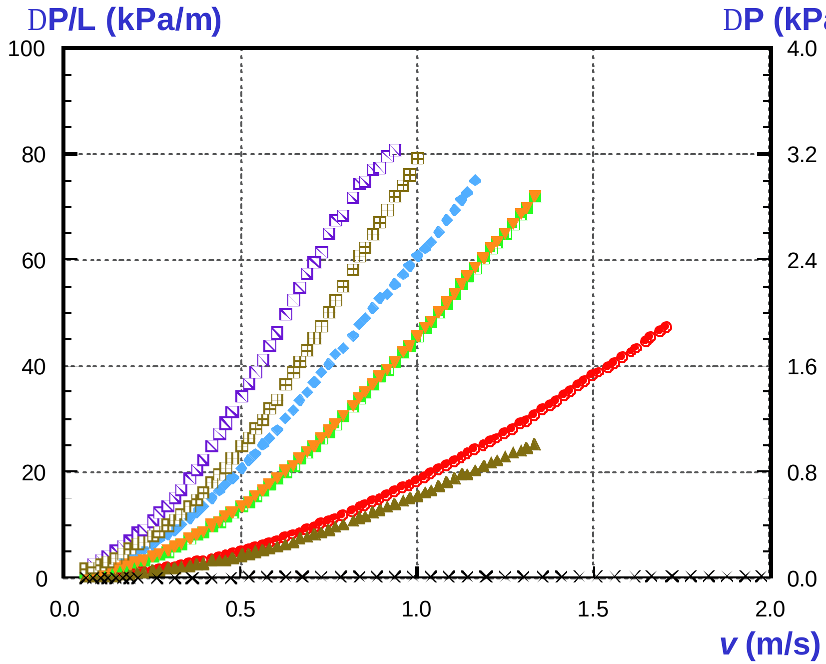
c_F	**Forchheimer coefficient**
K	**permeability**
L	**foam length**
v	**flow velocity**
Dp	**pressure difference**
m	**dynamic viscosity**
r	**fluid density**

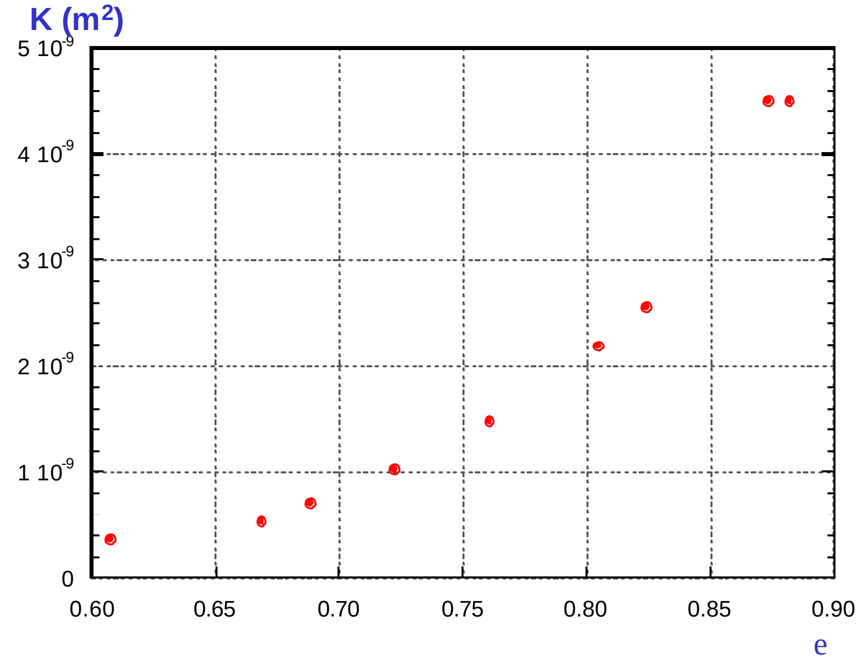
- Convection coefficient measured at plate

$$h'' = \frac{\dot{m} c \left(T_{w,outlet} - T_{w,inlet}\right)}{\left(T_{plate} - T_{w,inlet}\right) \bullet A_{foam-plate}}$$

A	**area**
c	**specific heat**
h''	**convection coefficient**
m	**mass flux**
T	**temperature**

Flow Characterization Experimental Results

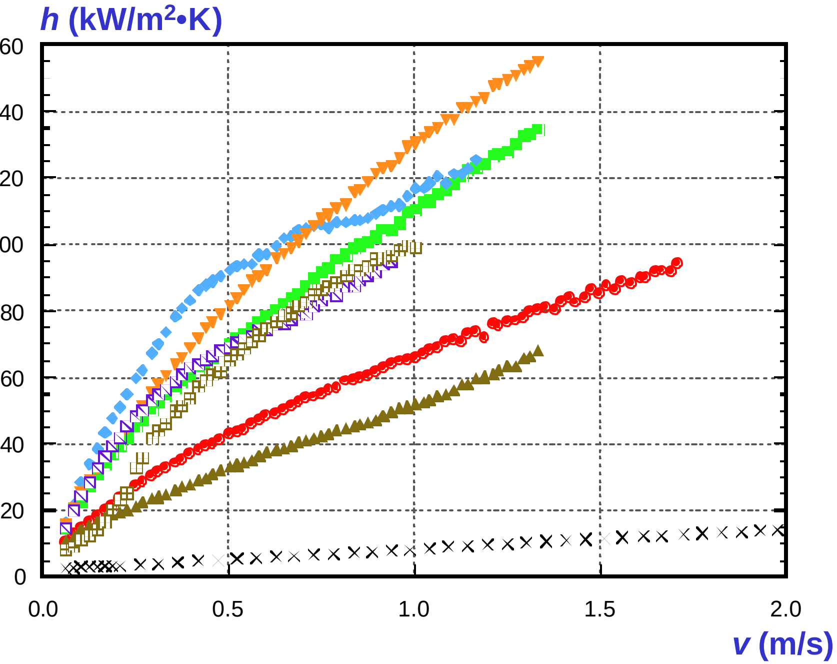


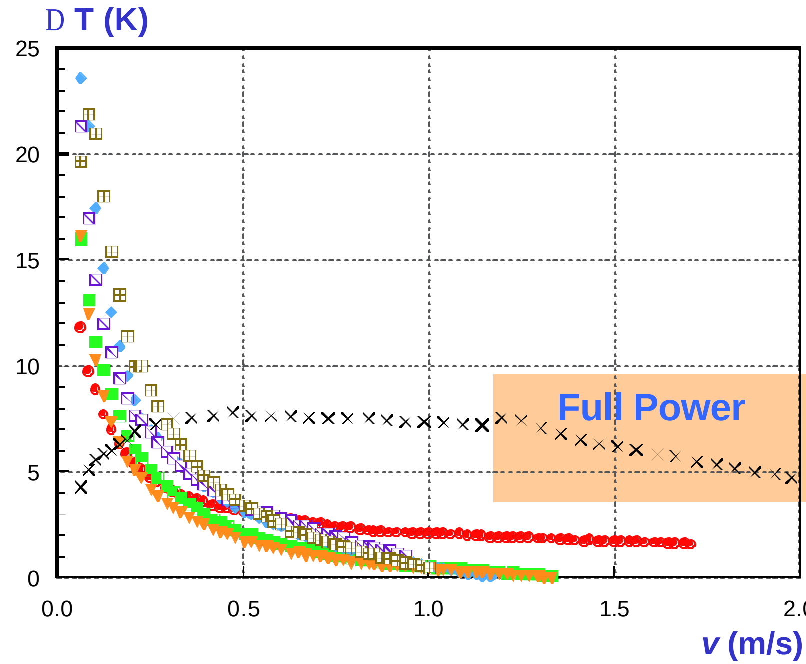


- Porosity decrease = pressure drop decrease
- Significant pressure drop compared to flat plate

- Monotonic increase of K with porosity
- Increase in sensitivity of K with increase in porosity

Heat Transfer Experimental Results

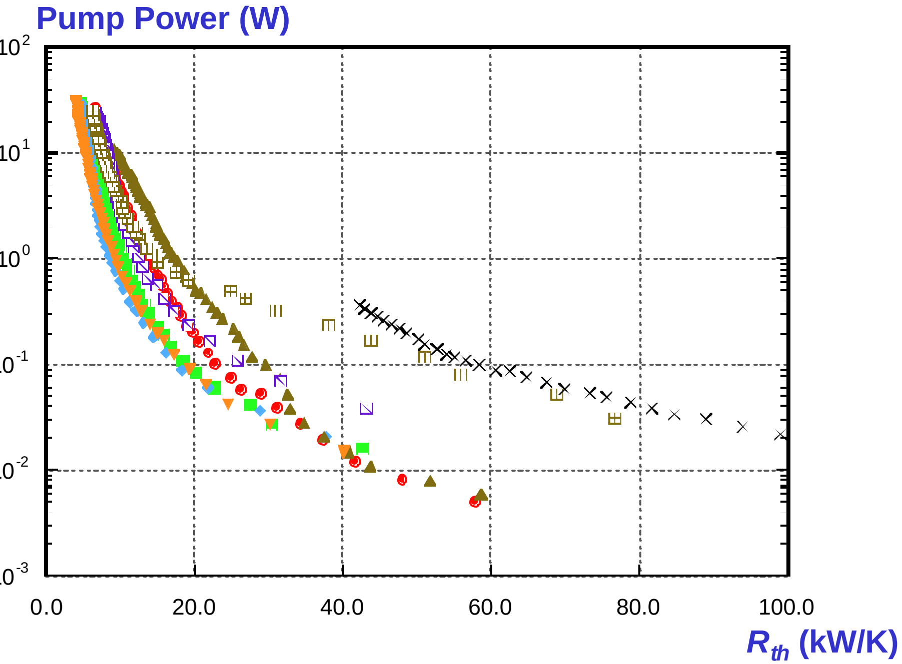


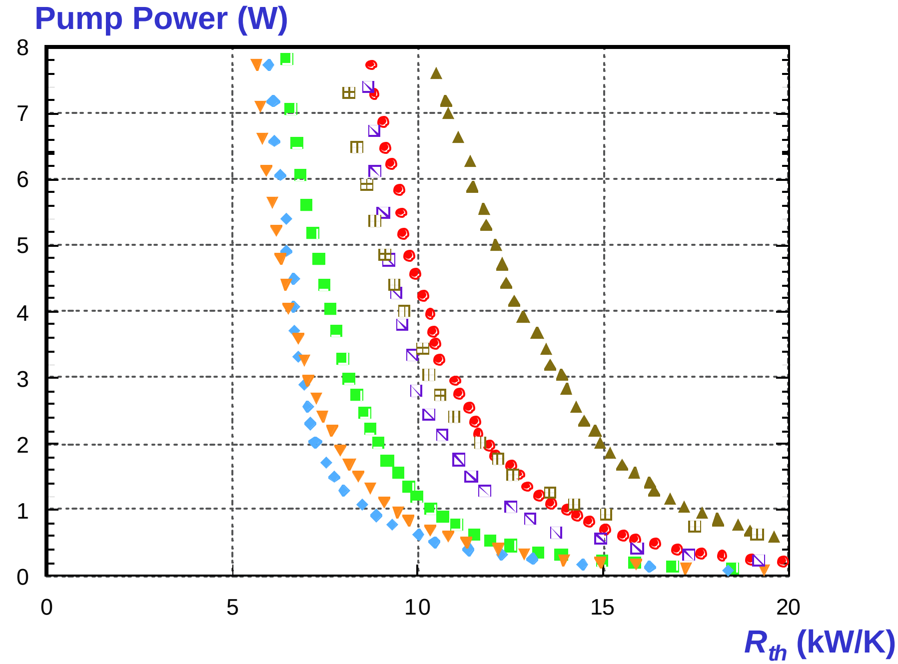


- Higher solid fraction provides a higher heat convection coefficient
- Results are independent of heater attachment

- Control of temperature gradient
- Poor performance by plate
- Note: Limited range for full power for the bare plate

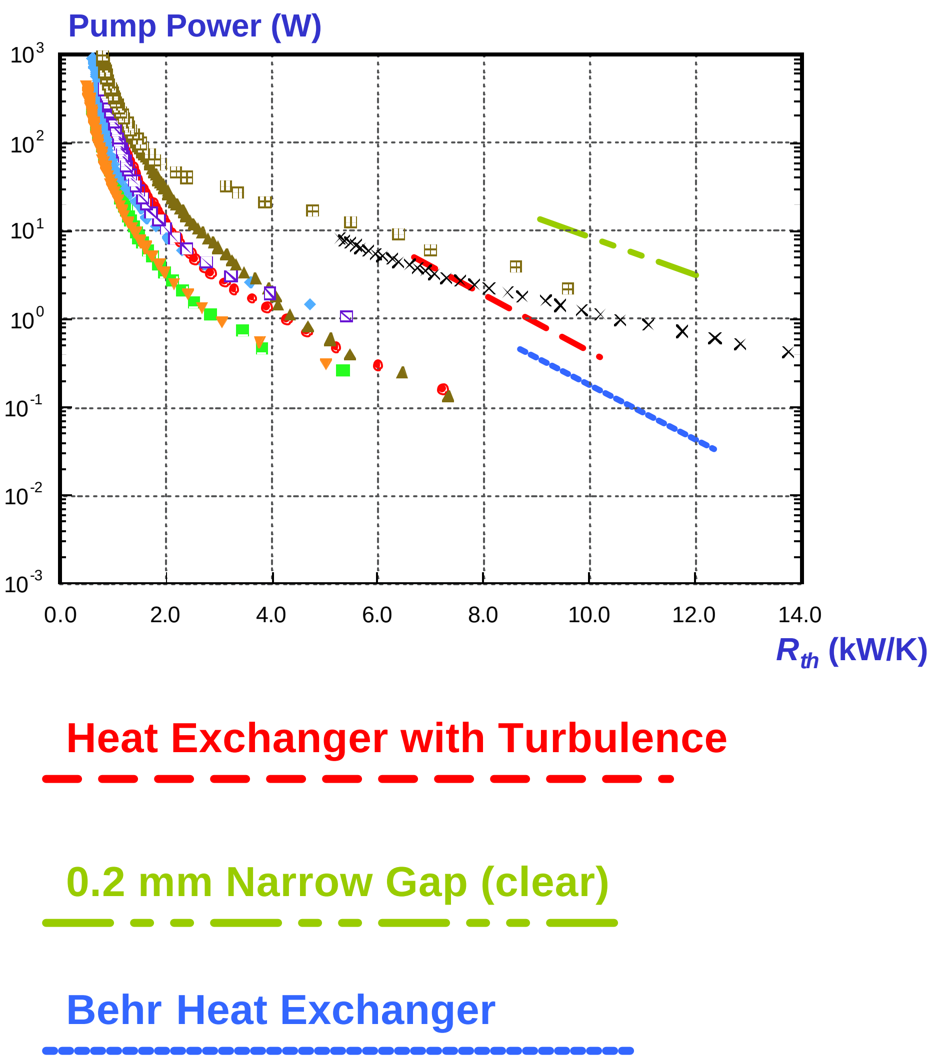
Power-Thermal Resistance Comparison





- Basis for real-world performance comparison
- Favorable power—thermal resistance curve
- Poor performance by bare plate
- Locate optimum configuration

Scaled Performance Comparison



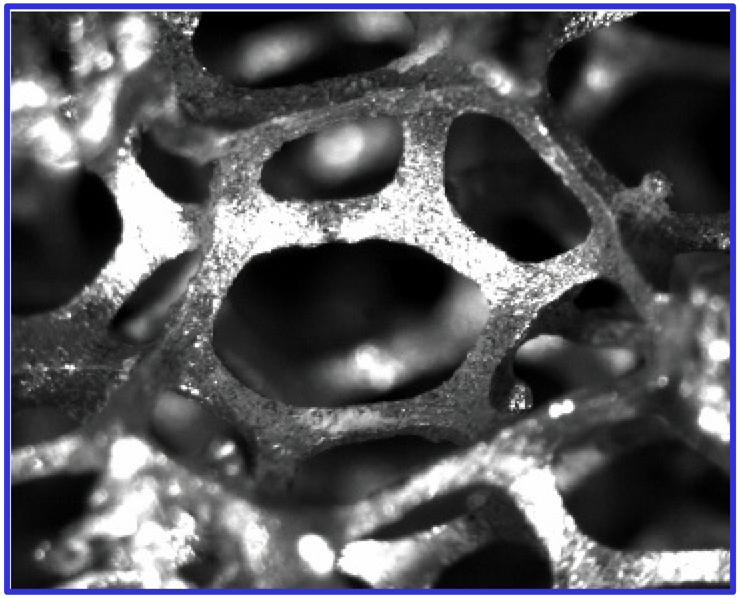
- Scaled to predict behavior with 50% ethylene glycol-water solution
- Assumptions/Considerations
  - Identical K and c_F
  - Similar operating temperature
  - Increase in flow rate compensates lower heat capacitance

Numerical Approaches

- Experimentally measure flow characteristics
  - Requires a wide variety of foam samples
  - Large time expenditure
  - Limited applicability
    - Foam configuration
    - Coolant type & flow rate range
- Pore-based analysis
  - Idealized three-dimensional solid matrix structure
  - Determine periodic flow behavior
  - Calculate interstitial convection coefficient

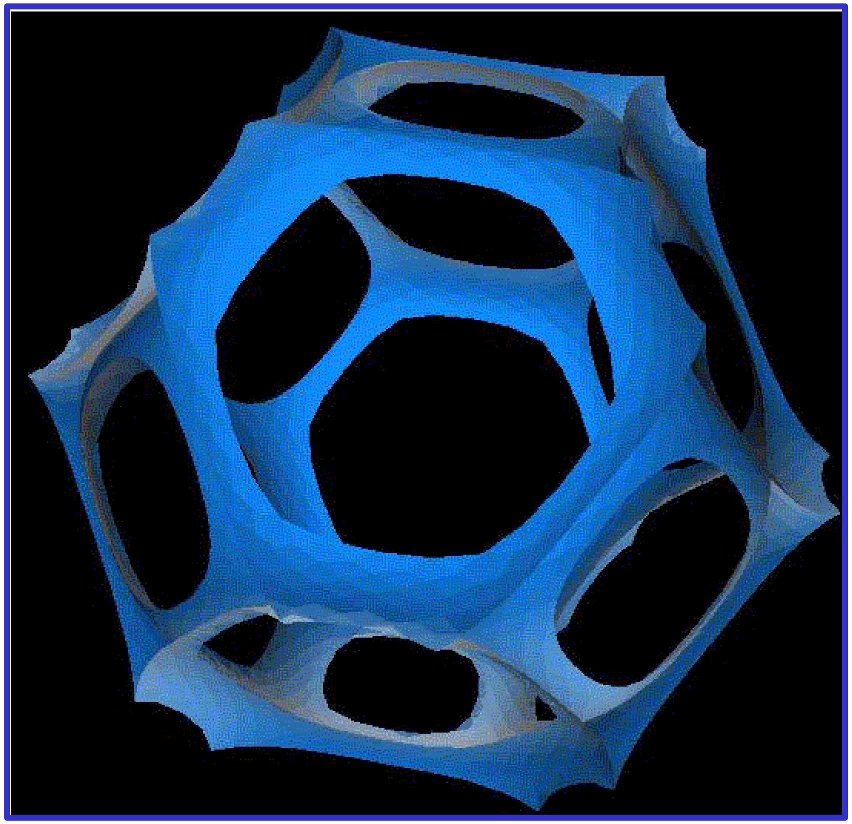
Foam Structure Idealization

- 14-sided tetrakaidecahedron
- Tetrahedral angle (~109º)
- Adjustments of shape



5 mm

Close-up of a single open cell



Model of the tetrakaidecahedron

Periodic Cell Boundary Conditions

- Periodic Length *L*
  - Velocity

$$\vec{V}(x,y,z) = \vec{V}(x+L,y,z) = \vec{V}(x+2L,y,z) = \ldots$$

  - Pressure

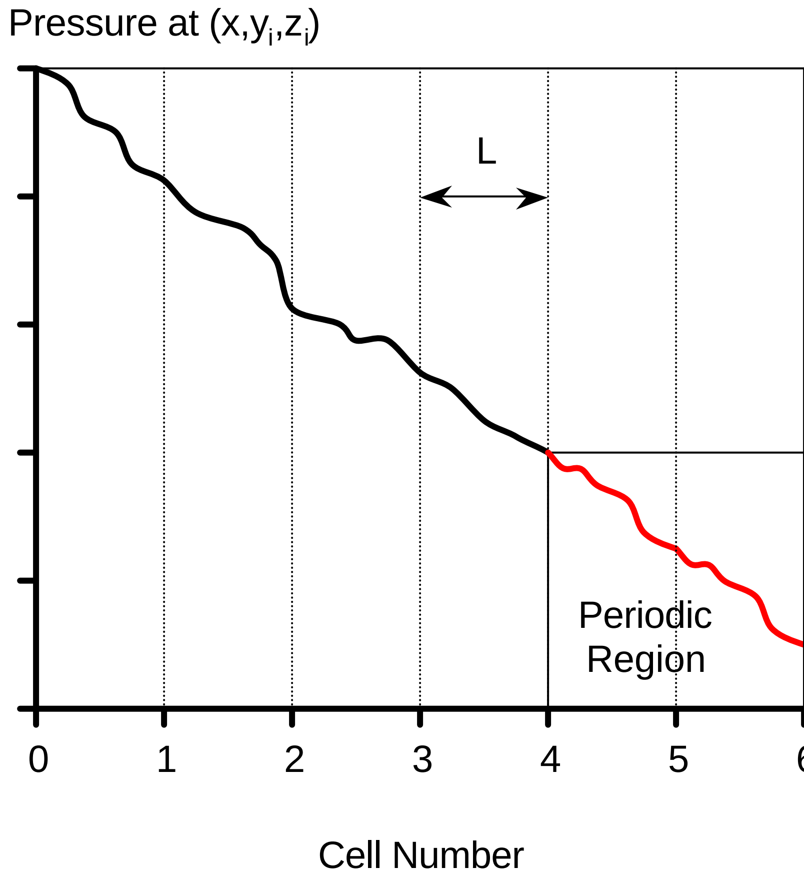
$$p_x(x,y,z) = -Bx + P(x,y,z)$$

where

$$B = \frac{p_x(x,y,z) - p_x(x+L,y,z)}{L}$$

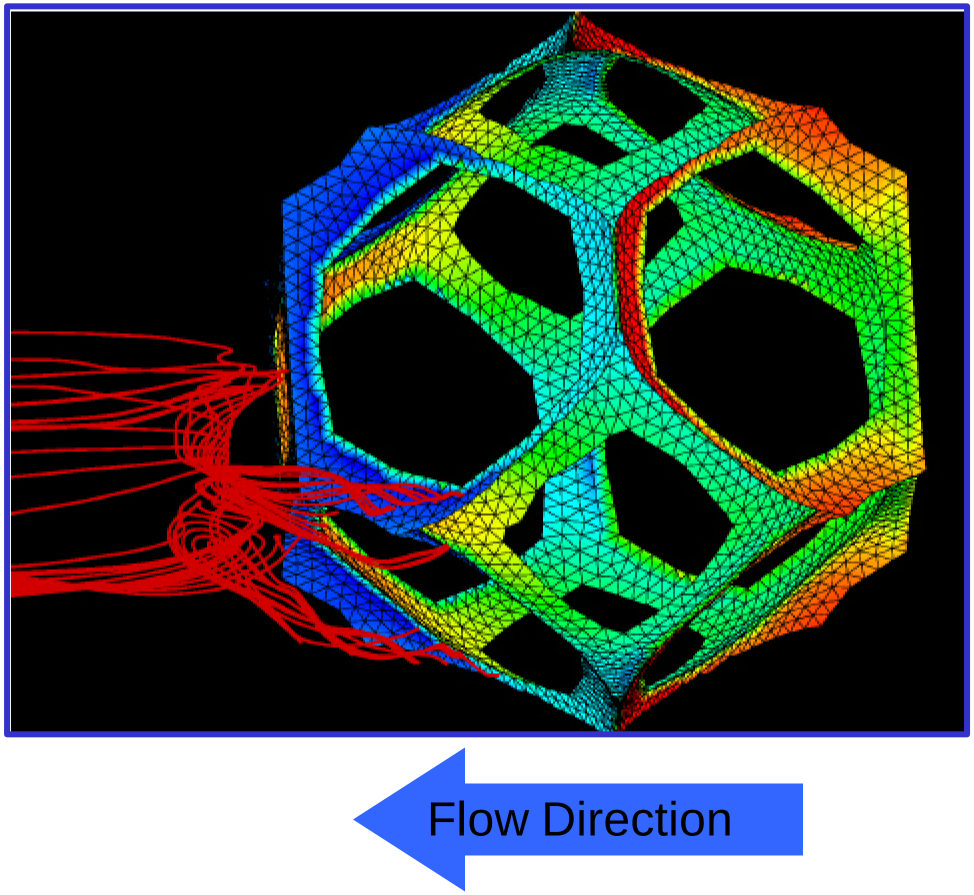
then

$$p_{y,z}(x,y,z) = p_{y,z}(x+L,y,z) = p_{y,z}(x+2L,y,z) = \ldots$$



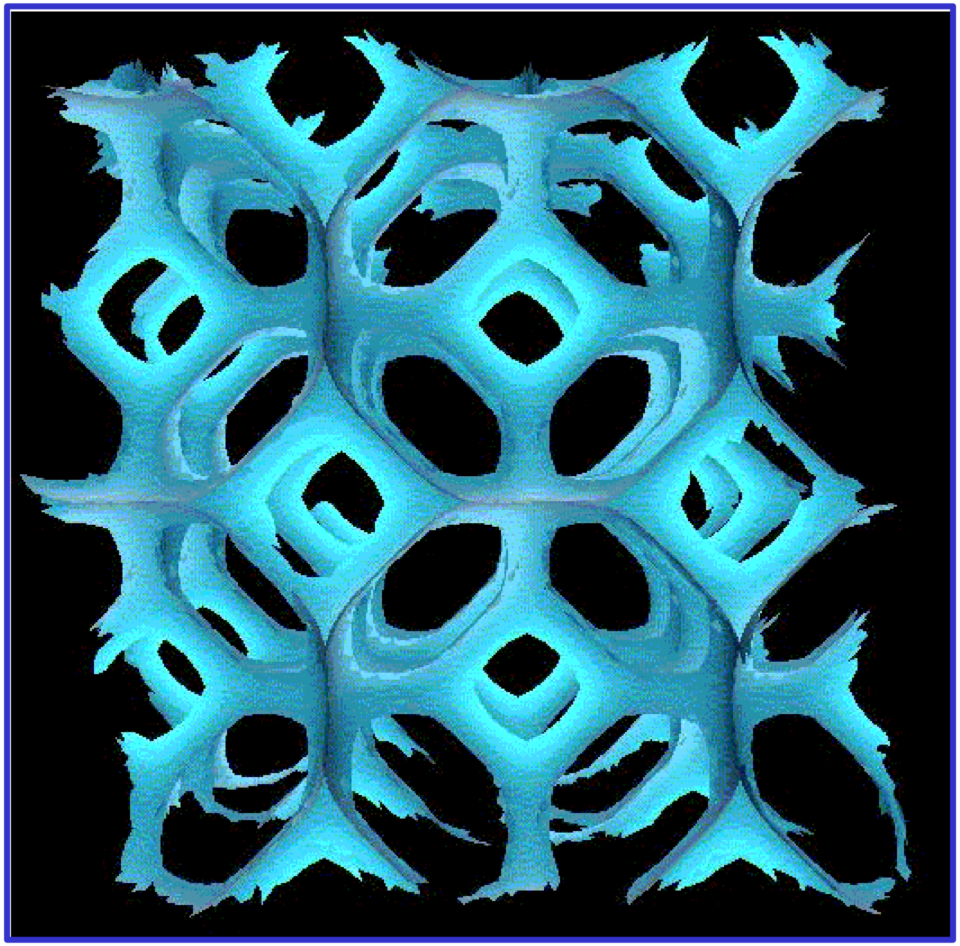
Visualization of the Flow Field

- Colored pressure gradient
- Red particle traces
- Non-turbulent flow
  - $Re_K < 100$ where
  - $Re_K = \rho V K^{½} \mu^{-1}$
- Vortex development in wake
  - Describe lack of “transitional range” in porous media
  - Insight into dispersion effects

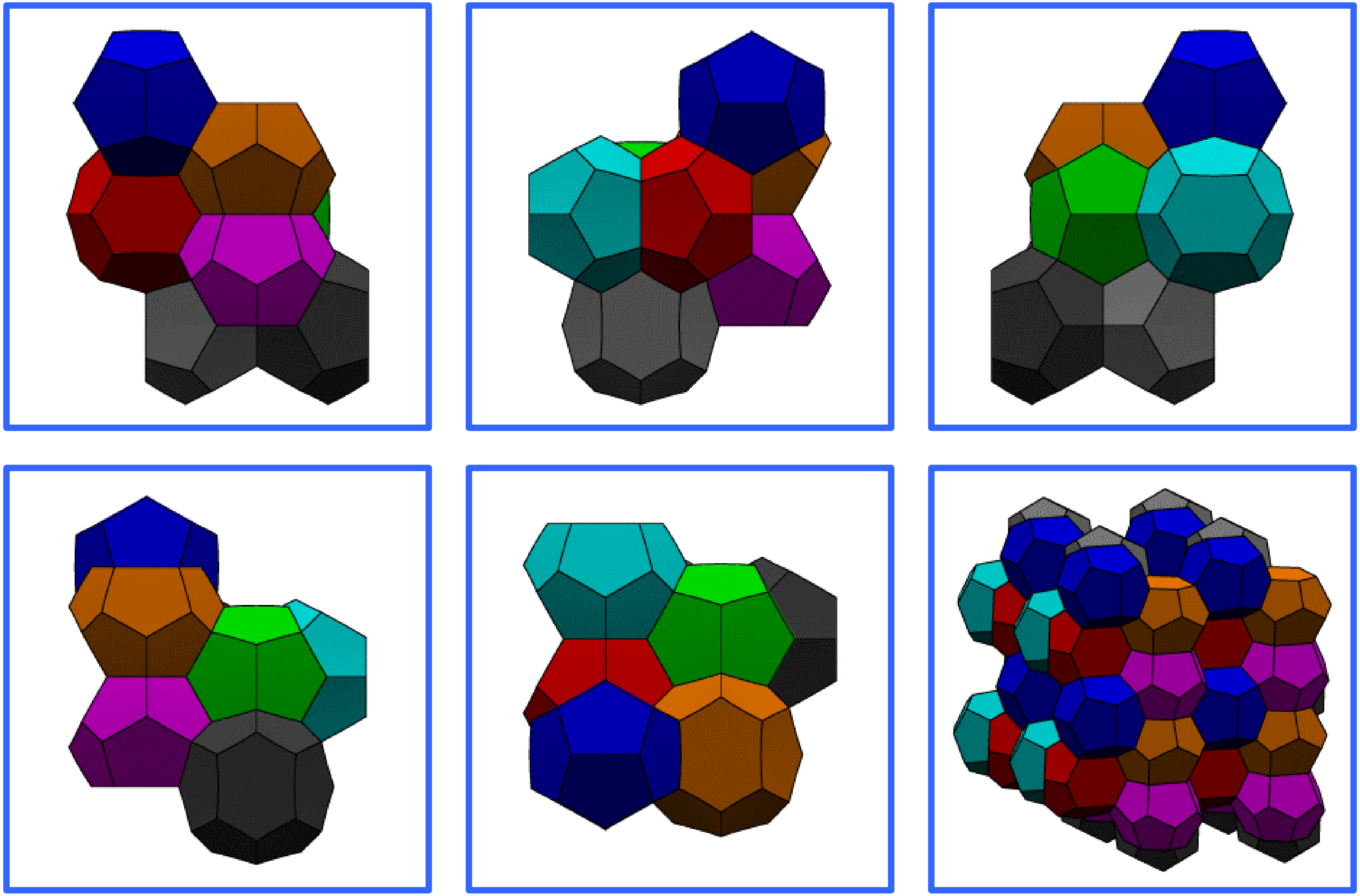


Periodic Configuration

- Tetrakaidecahedron base unit
- Not numerically optimized to minimize surface energy
- Possible tunneling effects
- Inconsistent porosity
- Improvement needed

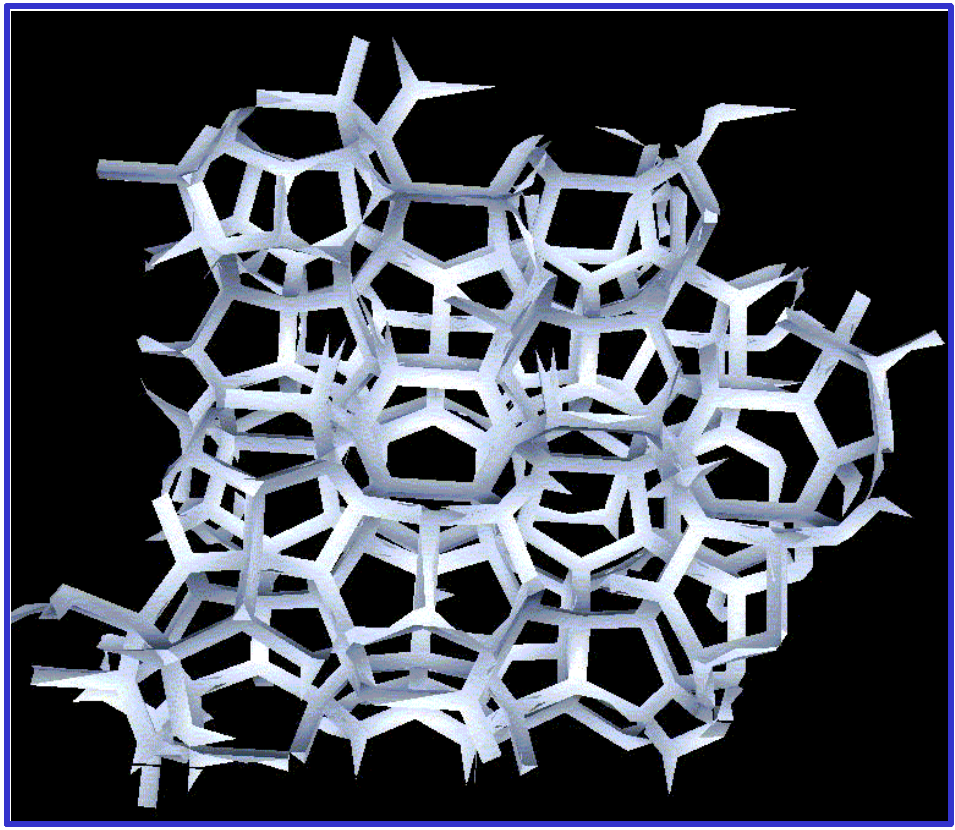


Improvement in Periodic Cell Representation



Wetted Form

- Wetted Weaire-Phelan form
- Numerically optimized surface energy
- 0.3% lower surface energy
- Composition
  - 8 equal volume cells
    - 2 dodecahedra
    - 6 fourteen sided figures
      - 2 hexagonal faces
      - 12 pentagonal faces



Conclusions

- Aluminum foam heat exchanger experiment:
  - Significantly higher heat convection coefficient
  - More uniform chip operating temperature
  - Favorable power input to thermal resistance curve
- Approach of pore-based numerical analysis
  - Analyze “transitional” region in porous media
  - Possibly directly calculate dispersion effects
  - Reduce extensive experimentation